

National Aeronautics and Space Administration



Future Missions & In Situ Resource Utilization (ISRU) Requirements

Presentation to
Keck Study Workshop
“New Approaches to Lunar Ice
Detection and Mapping”

July 22, 2013

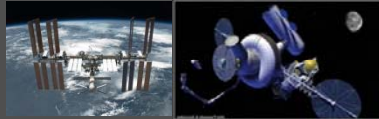
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Stepping Stone Approach for Demonstration & Utilization of Space Resources

Microgravity Processing & Mining

ISS & Space Habitats



ISRU Focus

- Trash Processing into propellants
- Micro-g processing evaluation
- In-situ fabrication

Purpose: Support subsequent robotic and human missions beyond Cis-Lunar Space

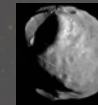
Near Earth Asteroids & Extinct Comets



ISRU Focus

- Micro-g excavation & transfer
- Water/ice prospecting & extraction
- Oxygen and metal extraction
- In-situ fabrication & repair
- Trash Processing

Phobos



ISRU Focus

- Micro-g excavation & transfer
- Water/ice and volatile prospecting & extraction

Purpose: Prepare for orbital depot around Mars

Purpose: Prepare for Phobos & future Space Mining of Resources for Earth

Planetary Surface Processing & Mining

Moon



ISRU Focus

- Regolith excavation & transfer
- Water/ice prospecting & extraction
- Oxygen and metal extraction
- Civil engineering and site construction

Purpose: Prepare for Mars and support Space Commercialization of Cis-Lunar Space

Mars



ISRU Focus

- Mars soil excavation & transfer
- Water prospecting & extraction
- Oxygen and fuel production for propulsion, fuel cell power, and life support backup
- Manufacturing & Repair

Purpose: Prepare for human Mars missions

What is Required to Utilize Space Resources?



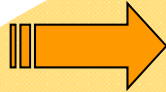
- **Understand the resources**
 - What resources are there (minerals, volatiles, water/ice)?
 - How abundant is each resource?
 - What are the areal and vertical distributions and hetero/homogeneity?
 - How much energy is required to locate, acquire and evolve/separate the resources?
- **Understand environment impact on extraction and processing hardware**
 - What is the local temperature, illumination, radiation environment?
 - What are the physical/mineralogical properties of the local regolith?
 - Are there extant volatiles that are detrimental to processing hardware or humans?
 - What is the impact of significant mechanical activities on the environment?
- **Design and utilize hardware to the maximum extent practical that has applicability to follow-on ISRU missions to utilize lunar volatiles (and other locations)**
 - Can we effectively excavate and transfer material for processing?
 - Can we effectively separate and capture volatiles of interest?
 - Can we execute repeated processing cycles (reusable chamber seals, tolerance to thermal cycles)?
 - Can we operate in shadowed areas for extended periods of time?

Space 'Mining' Cycle: *Prospect to Product*

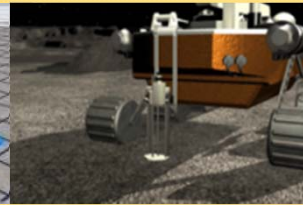
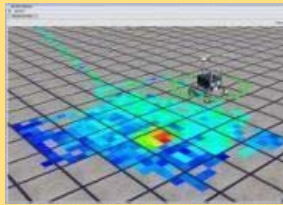


Resource Assessment (Prospecting)

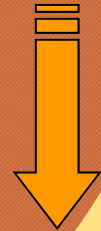
Global Resource Identification



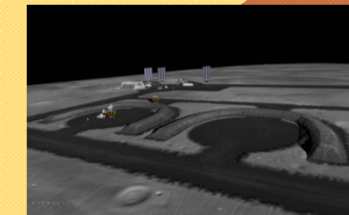
Local Resource Exploration/Planning



Mining



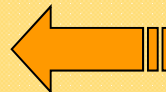
Maintenance & Repair



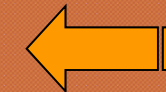
Site Preparation & Infrastructure Emplacement



Communication & Autonomy



Processing



Crushing/Sizing/Beneficiation



Spent Material Removal



Waste

Remediation



Power



Propulsion



Life Support & EVA



Depots



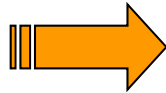
Product Storage & Utilization

Space 'Mining' Cycle: *Prospect*

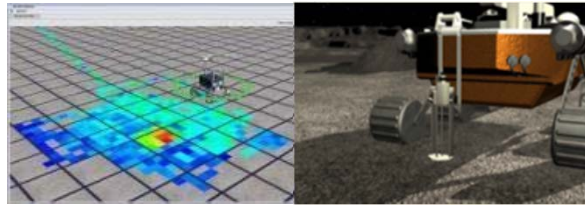


Resource Assessment (Prospecting)

Global Resource Identification



Local Resource Exploration/Planning



Possible Lunar ISRU Robotic Mission Sequence

Polar Resource/ISRU Proof-of-Concept Demo(s)



Purpose: Scout

- Understand and characterize the resources and environment at the lunar poles for science and ISRU
- Determine the 'economic' feasibility of lunar polar ice/volatile mining for subsequent use

Oxygen Extraction from Regolith/Solar Wind Volatiles



Critical Function Demo



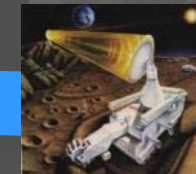
Polar Ice/Volatile Extraction

Purpose: Demo

- Verify critical processes & steps
- Verify critical engineering design factors for scale-up
- Address unknowns and Earth based testing limitations
- Characterize local material/resources
- Identify life issues



Pilot-Scale Operations



Purpose: Utilize

- Enhance or extend capabilities/reduce mission risk
- Verify production rate, reliability, and long-term operations
- Verify integration with other surface assets
- Verify use of ISRU products for full implementation

Which path depends on results of proof of concept mission(s)

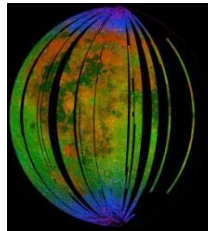
Global Assessment of Lunar Volatiles



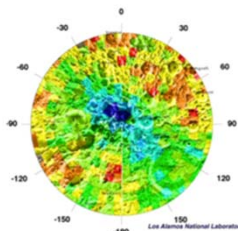
Apollo Samples



Moon Mineralogical Mapper (M³)



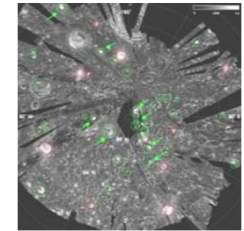
Lunar Prospector Lunar Recon Orbiter (LRO)



Lunar Crater Observation & Sensing Sat. (LCROSS)



Clementine Chandrayaan LRO Mini SAR/RF



	Solar Wind	Core Derived Water	Water/Hydroxyl	Polar Volatiles	Polar Ice
Instrument	Apollo samples Neutron Spectrometer	Apollo samples	M3/LRO	LCROSS	Mini SAR/RF
Concentration	Hydrogen (50 to 150 ppm) Carbon (100 to 150 ppm) Helium (3 to 50 ppm)	0.1 to 0.3 wt % water in Apatite 0 to 50 ppm water in volcanic glass	0.1 to 1% water; 1-2% frost in shadowed craters	3 to 10% Water equivalent Solar wind & cometary volatiles (CO, H₂, NH₃, organics)	Ice layers
Location	Regolith everywhere	Regolith; Apatite	Upper latitudes	Poles	Poles; Permanent shadowed craters
Environment	Sunlit	Sunlit	Low sun angle Permanent shadow <100 K	Low or no sunlight; Temperatures sustained at <100 K	<100 K, no sunlight
Depth	Top several meters; Gardened	Top 10's of meters	Top mm's of regolith	Below 10 to 20 cm of desiccated layer	Top 2 meters



Type and Scale of Prospecting Needed to Utilize Lunar Volatiles

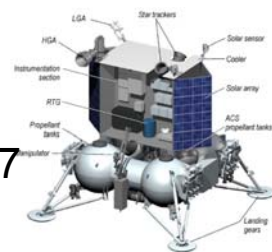


Exploratory Assessment

- Short duration mission:
 - 5 to 9 days
 - Hours in shadowed area
- Validate design and operation of hardware
- Evaluate physical and mineral properties of polar regolith
- Evaluate distribution of polar volatiles in 1 to 3 km area
 - Neutron & Near IR spectrometer
 - 3 to 5 cores; 1 to 2 meters deep
 - GC, MS & IR volatile measurements
- Validate site selection approach for locating volatiles at lunar poles
(missions to different destinations?)
Data sharing-competitors?)



Resource Prospector (RESOLVE)



Luna 25/27

Focused Assessment

- Long duration mission:
 - 6+ months
- Perform more extensive evaluation of volatile distribution in polar region: larger area and more samples
- Demonstrate extended operations in polar shadowed region
- Examine contaminants in water collected
- Validate site selected for long-term mining operations
- *Map the location & concentration of the lunar volatile resources*

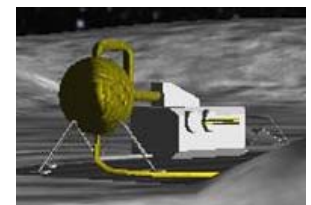
Economic Feasibility Assessment



RLEP-2 Type Mission

Mining Feasibility

- Demonstrate ISRU hardware for sustained excavation, processing, collection and storage of polar water and other volatiles of interest present
- Demonstrate water cleaning, and processing
- Demonstrate fuel production (from carbon-bearing volatiles)
- Demonstrate long-term storage of products (O₂, CH₄)
- Demonstrate power system for extended duration operations in polar shadowed region
- *Determine mining, transportation, infrastructure and logistics needs to sustain mining operations*



Resource Prospector Mission

Regolith & Environmental Science and Oxygen & Lunar Volatile Extraction (RESOLVE)



RPM is an internationally developed (NASA and CSA) mission/payload that that can perform two important missions for Science and Human Exploration of the Moon

Prospecting Mission: (Polar site)

- ✓ **Verify the existence of and characterize the constituents and distribution of water and other volatiles in lunar polar surface materials**
 - Map the surface distribution of hydrogen rich materials
 - Determine the mineral/chemical properties of polar regolith
 - Measure bulk properties & extract core sample from selected sites
 - To a depth of 1m with minimal loss of volatiles
 - Heat multiple samples from each core to drive off volatiles for analysis
 - From <100K to 423 K (150° C)
 - From 0 up to 100 psia (reliably seal in aggressively abrasive lunar environment)
 - Determine the constituents and quantities of the volatiles extracted
 - Quantify important volatiles: H₂, He, CO, CO₂, CH₄, H₂O, N₂, NH₃, H₂S, SO₂
 - Survive limited exposure to HF, HCl, and Hg

ISRU Processing Demonstration Mission: (Equatorial and/or Polar Site)

- ✓ **Demonstrate the Hydrogen Reduction process to extract oxygen from lunar regolith**
 - Heat sample to reaction temperature
 - From 150° C to 900° C
 - Flow H₂ through regolith to extract oxygen in the form of water
 - Capture, quantify, and display the water generated

Resource Prospector Mission



Sample Acquisition –

Auger/Core Drill [CSA provided]

- Complete core down to 1 m; Auger to 0.5 m
- Minimal/no volatile loss
- Low mass/power (<25 kg)
- Wide variation in regolith/rock/ice characteristics for penetration and sample collection
- Wide temperature variation from surface to depth (300K to <100K)

Sample Evaluation –

Near Infrared Spectrometer (NIR)

- Low mass/low power for flight
- Mineral characterization and ice/water detection before volatile processing
- Controlled illumination source

Resource Localization –

Neutron Spectrometer (NS)

- Low mass/low power for flight
- Water-equivalent hydrogen ≥ 0.5 wt% down to 1 meter depth at 0.1 m/s roving speed

Volatile Content/Oxygen Extraction –

Oxygen & Volatile Extraction Node (OVEN)

- Temperature range of <100K to 900K
- 50 operations nominal
- Fast operations for short duration missions
- Process 30 to 60 gm of sample per operation (Order of magnitude greater than TEGA & SAM)

Volatile Content Evaluation –

Lunar Advanced Volatile Analysis (LAVA)

- Fast analysis, complete GC-MS analysis in under 2 minutes
- Measure water content of regolith at 0.5% (weight) or greater
- Characterize volatiles of interest below 70 AMU

Operation Control –

Flight Avionics [CSA/NASA]

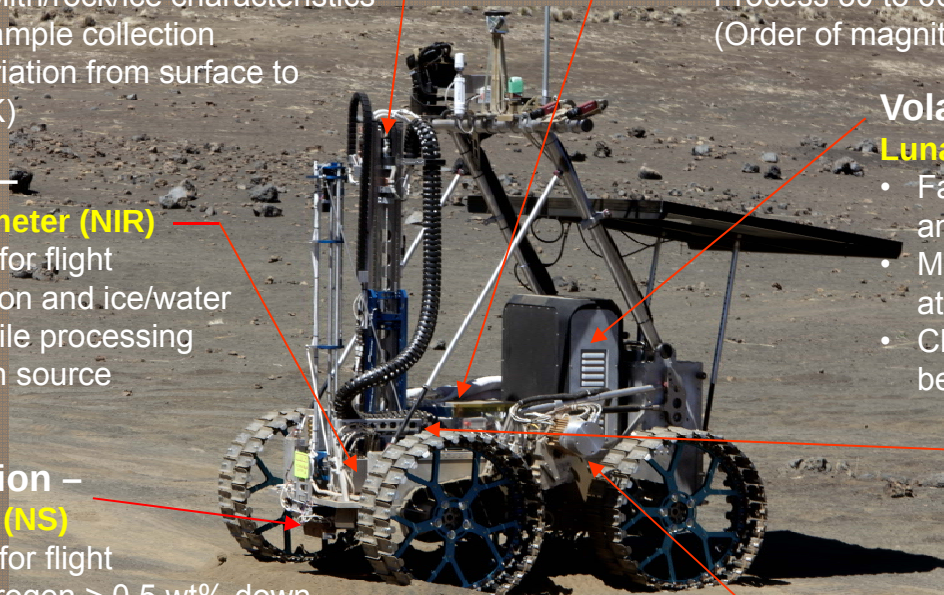
- Space-rated microprocessor

Surface Mobility/Operation [CSA mobility platform]

- Low mass/large payload capability
- Driving and situation awareness, stereo-cameras
- Autonomous navigation using stereo-cameras and sensors
- NASA contributions likely for communications and thermal management

RESOLVE Instrument Suite Specifications

- Nom. Mission Life = 10+ Cores, 12+ days
- Mass = 60-70 kg
- Dimensions = w/o rover: 68.5 x 112 x 1200 cm
- Ave. Power; 200 W



Lunar Resource Prospecting Instruments

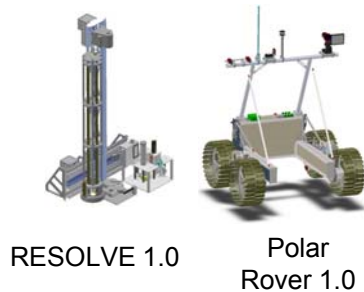


Instrument Suite Recommended for RLEP-2	RESOLVE	Luna 27	Optimal Prospector
Lander Instruments Stereo Imaging System Beacon (navigation/data reference) Langmuir probe (levitated dust) Particle counter (levitated dust) Electron Paramagnetic Resonance Spectrometer (determine reactivity of dust for biologic implications) Sample Processing System Arm/Scoop Geotechnical End Effectors Magnets (for magnetic susceptibility)	360° camera capability	TV imaging X Dust measurements GC/MS and Laser MS Possible arm/scoop Drill (2 m) Mineral Eval: IR, UV, and optical imaging Regolith thermal property measurement Plasma/neutrals measurement Sesimic activity measurement	X X Sesimic for subsurface features
Mobile Instruments Stereo Imaging System Neutron Spectrometer Ground Penetrating Radar Drill (2 m) Arm/Scoop Geotechnical End Effectors Magnets (for magnetic susceptibility) Sample Processing System GC/MS Tuneable Diode Laser	Navigation and sample site imaging X X (1 m) Measure while drilling X X Mineral and H ₂ O/OH Eval: Near IR		X X X X X Regolith thermal measurement Sesimic receiver X X Multiple mineral instruments and microscope

Possible Evolution of Surface Systems - Finding to Utilizing Polar Water/Volatiles

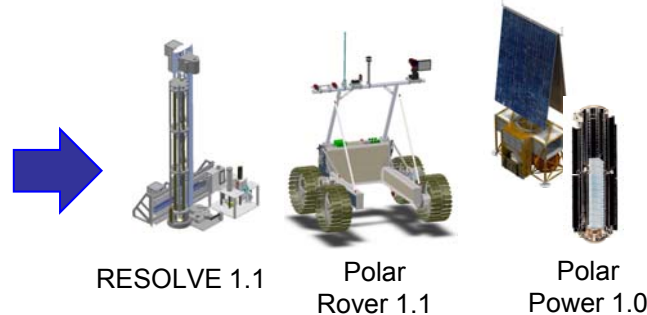


RPM Mission 1 Exploratory Assessment



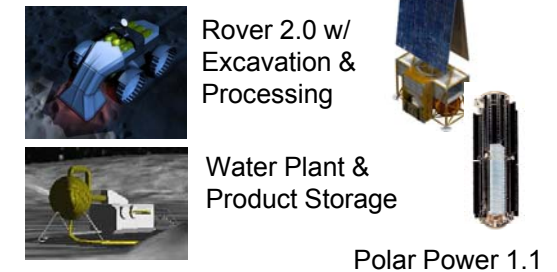
- Short Duration Mission
 - Short duration in shadowed area (hrs)
- Validate design and operation of hardware
- Evaluate distribution of polar volatiles in 1 to 3 km area
- Validate site selection approach for locating volatiles at lunar poles

RPM Mission 2 Focused Assessment



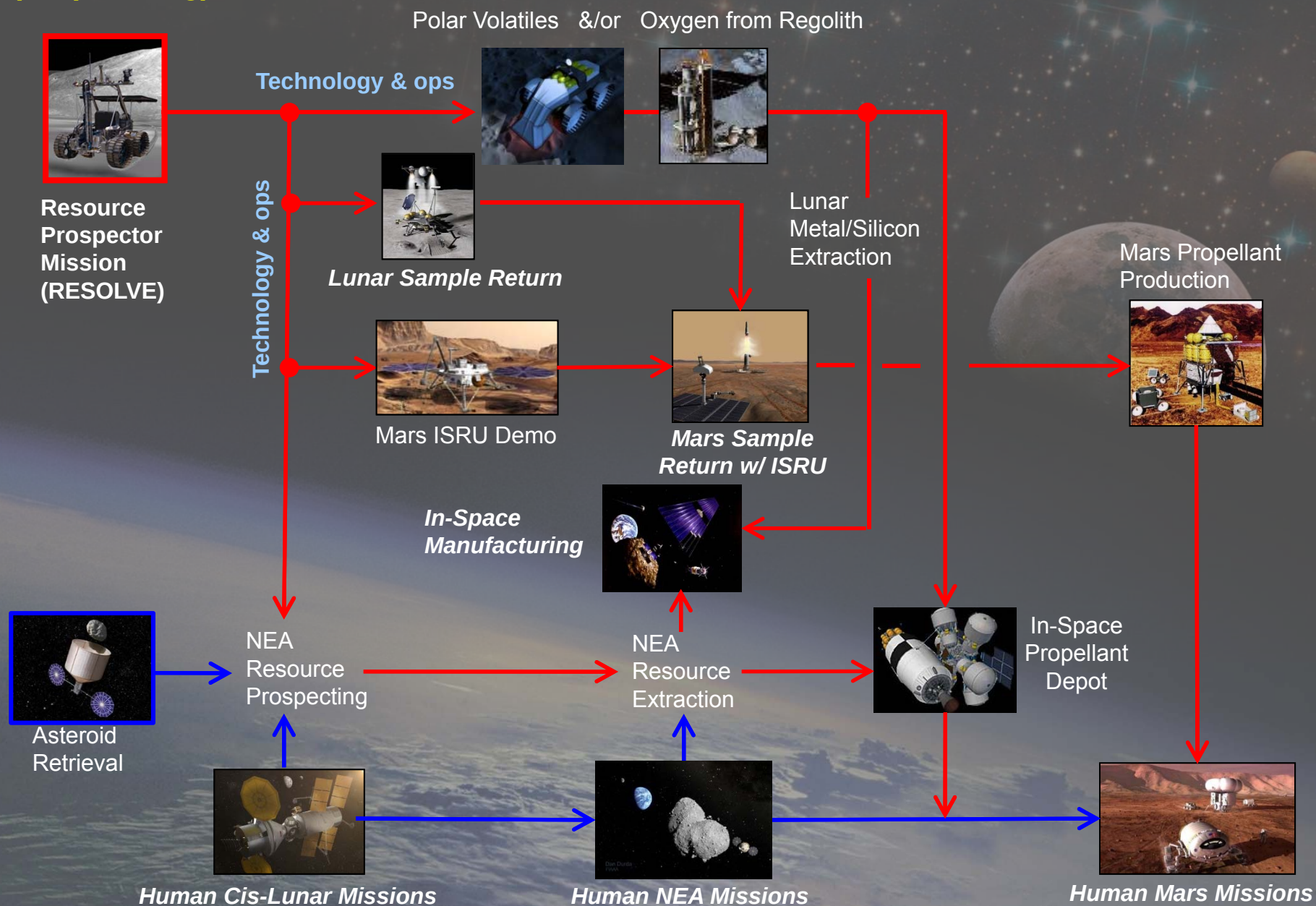
- Upgrade rover for longer term operation on the Moon and in shadowed areas
- Perform more extensive evaluation of volatile distribution in polar region: larger area/more samples
- Upgrade physical/mineral instruments
- Examine purity of water collected & possibly test cleaning technique
- Demonstrate power system for extended duration operations in polar shadowed region (*Note: mass estimate is based on remainder of lander payload capability*)

IceMiner Mission Mining Feasibility



- Finalize polar rover design (tandem rover possible)
- Demonstrate ISRU hardware for sustained excavation, processing, and collection of polar water/volatiles
- Demonstrate water cleaning, processing, and storage
- Demonstrate fuel production (from carbon-bearing volatiles)
- Upgrade power system for polar operations
 - *Note: Size of stationary processing unit will be a function of lander payload and desired processing scale*

(for planning)



ISRU Development Areas vs Mission Applications



ISRU Development Areas	Resource Prospector (Moon, Mars, NEO)	Atmosphere Processing (Mars)	Regolith/Soil Processing for Water (Moon, Mars, NEO)	Material Processing for Oxygen/Metals (Moon, NEO)	Trash Processing to Fuel
Regolith-Soil Extraction					
Regolith (granular) Excavation & Transfer	X		X	X	
Hard Material Excavation & Transfer	P			P	P
Hydrated Soil /Material Excavation & Transfer	P		X	X	X
Icy-Soil Excavation & Transfer	X		X	X	
Resource Characterization					
Physical Property Evaluation	X				
Mineral/Chemical Evaluation	X			X	
Volatile-Product Analysis	X	X			X
Regolith-Soil Processing (Volatiles, O₂, Metal)					
Crushing			P	X	P
Size Sorting				P	
Beneficiation/Mineral Separation				P	
Solid/Gas Processing Reactor	X		X	X	X
Solid/Liquid Processing Reactor				P	
Contaminant Removal			X	X	X

ISRU Development Areas	Resource Prospector (Moon, Mars, NEO)	Atmosphere Processing (Mars)	Regolith/Soil Processing for Water (Moon, Mars, NEO)	Material Processing for Oxygen/Metals (Moon, NEO)	Trash Processing to Fuel
Gas Processing					
Dust/Particle Filtration		X	X	X	X
CO ₂ Capture - Separation		X		P	X
CO ₂ Conversion into CO-O ₂		P			
CO/CO ₂ Conversion into H ₂ O-CH ₄		P		P	X
H ₂ -CH ₄ Separation		P		P	X
Water Processing					
Water Capture	X		X	X	X
Water Cleanup - Purity Measurement			X	X	X
Water Electrolysis		P	X	P	X
Regenerative Dryers		P	X	P	X
Support Systems					
Extended Operation Power Systems			P	P	
Extended Operation Thermal Systems			P	P	
Cryogenic Liquefaction, Storage, and Transfer					

P = Possible need

Main Discriminators: material (physical, mineral) water content/form (ice, hydration, surface tension), gravity (micro, low), pressure, (vacuum, atm.), and weathering

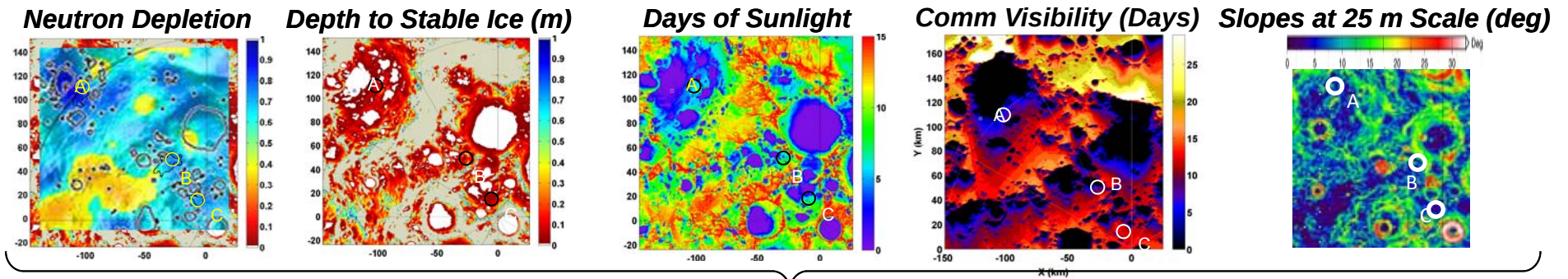
Questions?



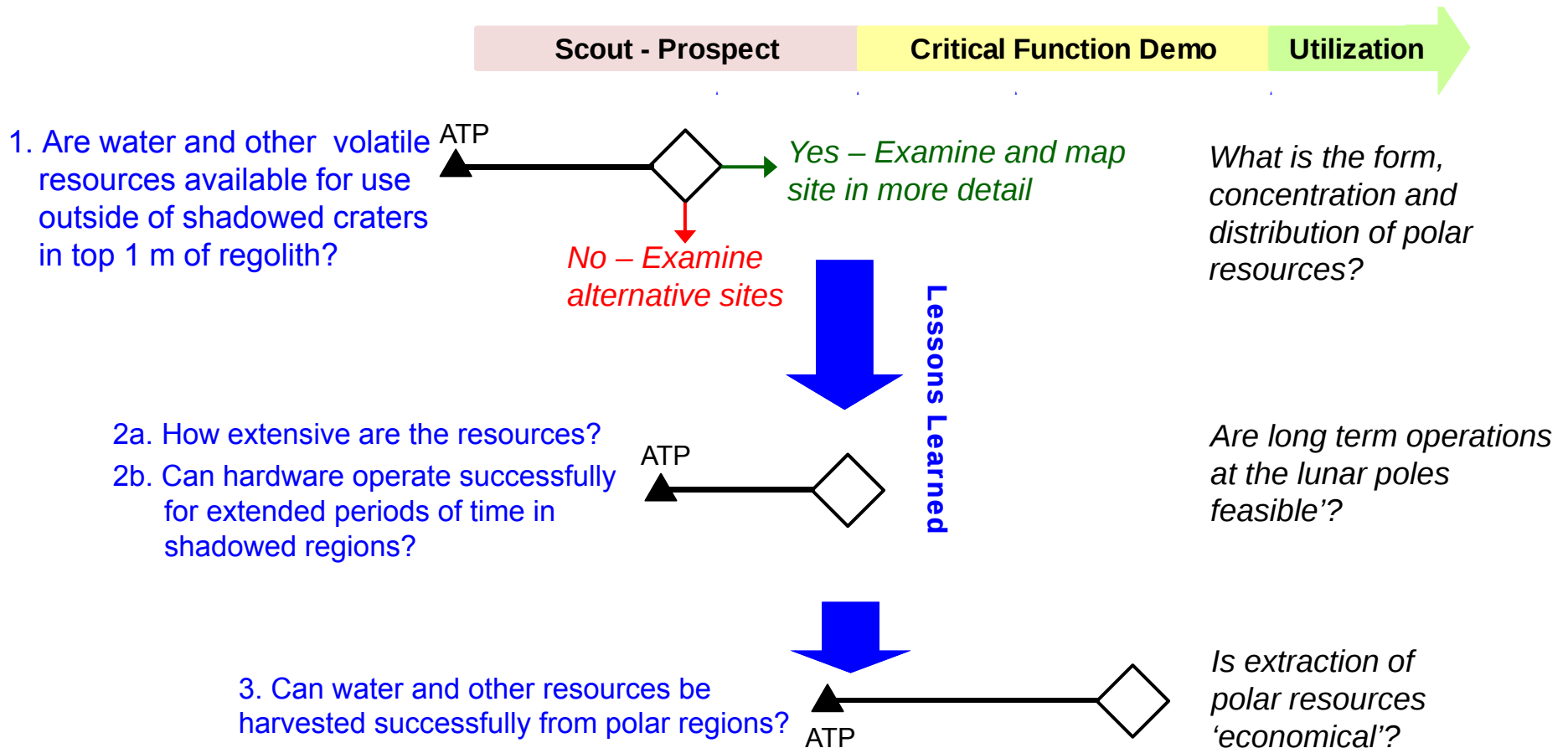


Backup

Lunar Volatile Site Selection - Prospecting Cycle



Approach to Understanding Polar Volatile Resources and Retiring Risk is Required



Key RESOLVE Mission Design Trades

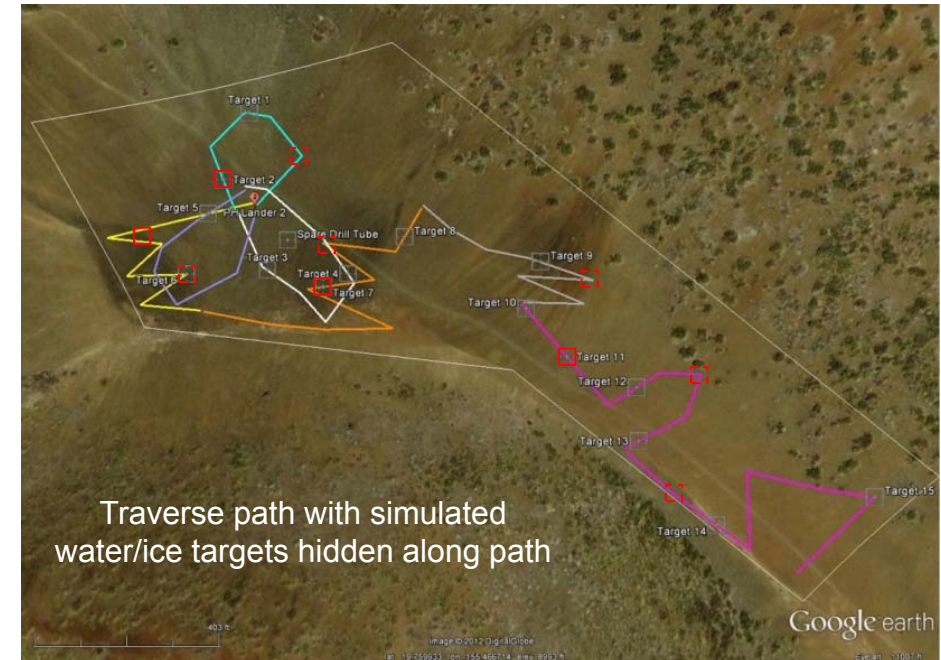
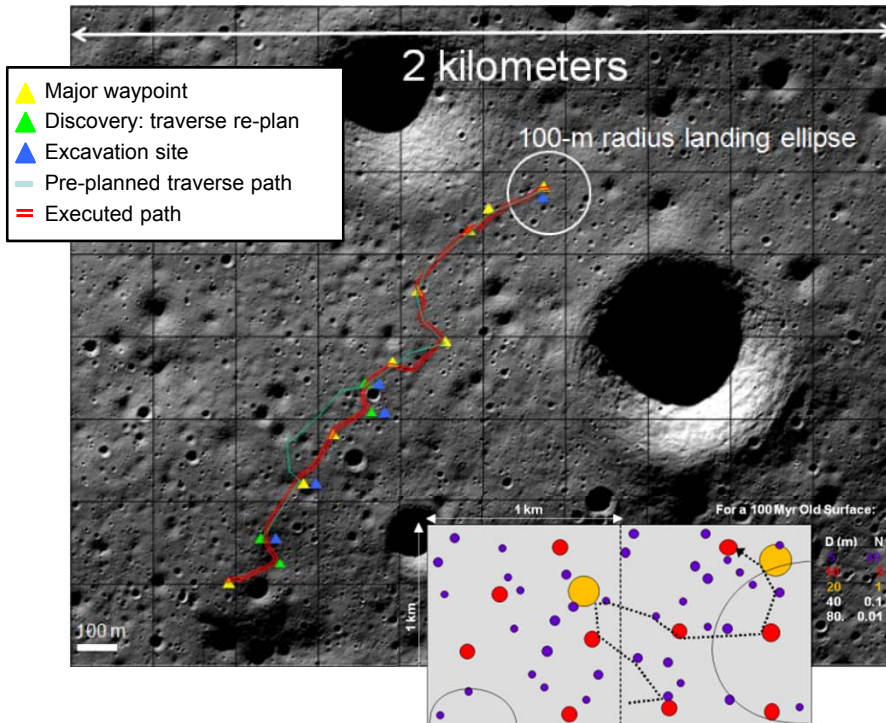


Mission Attributes	Base	Mid	Full
Location	Long duration sunlight	Min. Sun/Shadowed	Permanent Shadow
Sample Site Selection	Surface features/minerals	Neutron Spec on Rover	Neutron Spec with GPR
Subsurface Sample Acquisition	Arm/scoop	<i>Auger w sample transfer</i>	Core Drill/Push Tube w sample transfer
Sample of Interest	Rock/regolith	Ice	Polar volatiles
Sample Depth	<i><0.75 m</i>	1.0 m	2.0 m
Sample Measurement	Downhole Optical for ice	Oven w Tunable Diode Lasers	Oven with GC/MS and Near IR
Sample Preparation	None	Crushing	Thin Section
Mineral Characterization	None	Single instrument - Near IR	Multiple Instruments
Regolith/Dust Physical Characterization	None	Camera & Drill Response	Microscope & Geotechnical Instruments
Volatile/Product Collection	None	Water	Water and gas volatiles
Oxygen Extraction from Regolith	None	H₂ Reduction w Same Oven	Separate demo
Temperature/Radiative Environment Characterization	None	External temp sensor	Instrumented Radiator
Mobility	None - Lander	Hopper	Rover
Power	<i>Non-recharge battery</i>	Battery/Solar Array	Nuclear
Communications	Direct to Earth-rover	<i>Direct to Earth-lander; rover relay</i>	Comm Relay Satellite

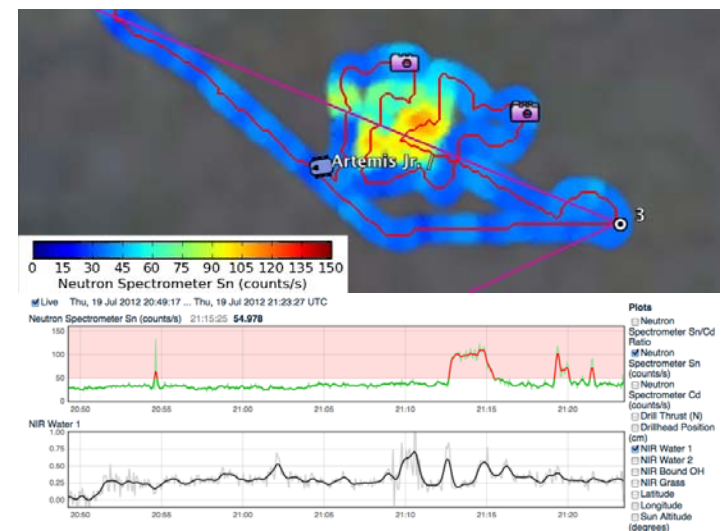
Blue Bold = Baseline

Red Italics = Backup

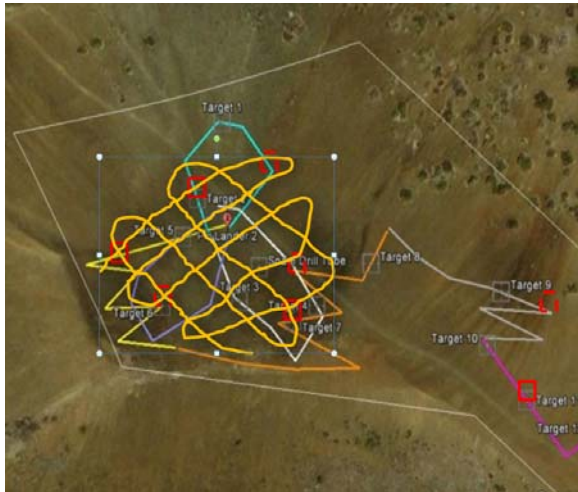
Exploratory Prospecting for Lunar Volatiles



- Hypothesize location of volatiles based global data, terrain, and geological context
- Plan traverse before landing based on location estimates and rover capabilities
- Utilize non-invasive surface and subsurface instruments to guide selection of sample sites; Instrument suite may be limited
- Perform coring and volatile analysis at selected locations
- Re-plan traverse based on accumulations of results and new hypotheses



Focused Resource Assessment of Polar Volatiles



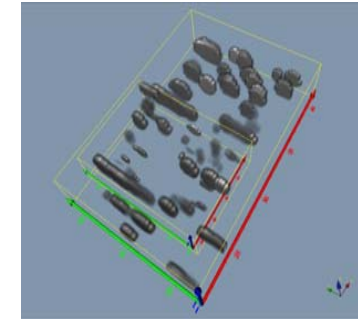
Traverse paths to fill in missing data



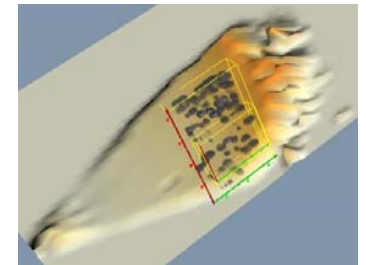
Rover-Data
localization
equipment



Rovers performing coordinated
area assessment



Data fusion with terrain
information



- Plan a more extensive and thorough traverse based on filling in holes in data gathered from the Exploratory Assessment; Utilize multiple rovers if possible for redundancy and greater coverage (multinational?)
- Utilize more extensive instrument suite if possible to gather greater data on both volatile location and characteristics
 - Besides NS and Near IR, potentially include GPR and more mineral/physical instruments
- Utilize more instruments to assess volatiles and potential contaminants released and condensed with water
- Build 3-D interpretation of data as it is collected; utilize to redirect traverse and data sampling activities
- Utilize extended operations to provide lessons learned for
 - Designing mining feasibility hardware
 - Establishing operation protocols and procedures for remote mining
 - Verifying communications, localization, and situational awareness

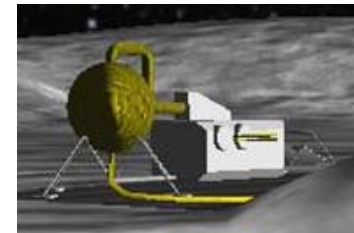
Mining Feasibility for Polar Volatiles



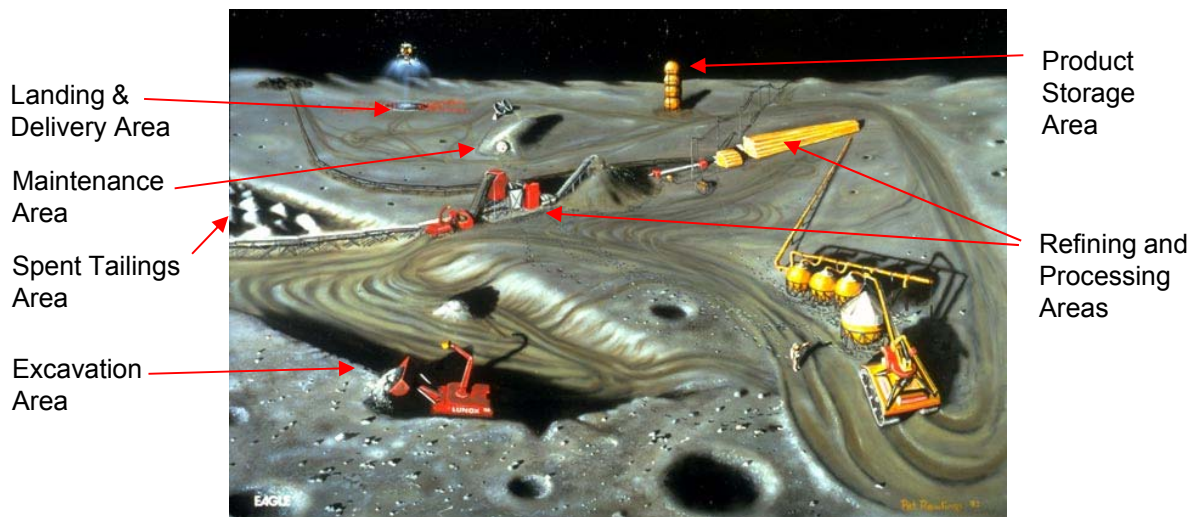
- Demonstrate critical mining and processing hardware
 - Finalize polar rover/mobility design for subsequent mining operations
 - Demonstrate ISRU hardware for sustained excavation, processing, and collection of polar water/volatiles
 - Demonstrate water cleaning, processing, and storage that can be scaled up to mining rates
 - Demonstrate fuel production from carbon-bearing volatiles if present
 - Demonstrate power system for sustained operations
- Finalize operation protocols and procedures for remote mining
- Establish mine infrastructure and operation area layout
- Establish benchmarks for logistics, mean-time between failures, etc.



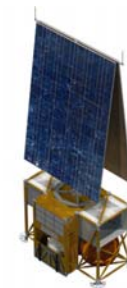
Polar Mobility, Excavation & Processing



Water Plant & Product Storage



Plan for Mine/Infrastructure Layout & Operation



Polar Power System